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PERFORMANCE OF A 48-MODULE SWIRL-CAN TURBOJET COMBUSTOR SEGMENT AT HIGH TEMPERATURES USING ASTM-A1 FUEL

by Richard W. Niedzwiecki and Harry M. Moyer

Lewis Research Center
Cleveland, Ohio

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16. Abstract

A turbojet combustor consisting of an array of swirl-can modules was evaluated in a rectangular duct at temperature levels encountered in advanced engines. Performance was evaluated at inlet air temperatures of 600° and 1150° F (589 and 894 K), a pressure of 3 atm, and reference velocities up to 180 ft/sec (54.9 m/sec). Combustion efficiencies were 100 percent at combustor exit temperatures near 2200° F (1477 K). Overall pressure loss was 6 percent at a diffuser inlet Mach number of 0.25 and an exit- to inlet-temperature ratio of 2.5. The exit temperature pattern factor varied from 0.19 to 0.24, decreasing with increasing inlet temperature. Altitude blowout and relight tests were conducted at a combustor reference Mach number of 0.1, a fuel-air ratio of 0.015, and inlet air temperatures and pressures of 100° to 700° F (311 to 644 K) and 0.5 to 3.0 atm, respectively.

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SUMMARY

A rectangular combustor consisting of an array of 48 swirl-can modules was evaluated at temperature levels encountered in advanced engines. Combustion tests were conducted at inlet air temperatures of 600° and 1150° F (589 and 894 K), a pressure of 3 atmospheres, and combustor reference velocities up to 180 feet per second (54.9 m/sec).

Combustion efficiencies were 100 percent at combustor exit temperatures near 2200° F (1478 K). Overall pressure loss (including diffuser loss) was 6 percent at a diffuser inlet Mach number of 0.25 and a combustor exit- to inlet-temperature ratio of 2.5. Good circumferential and radial combustor exit temperature distributions were obtained. The pattern factor varied from 0.19 to 0.24, decreasing with increasing inlet temperature and temperature rise.

Altitude blowout and relight tests were conducted at a combustor reference Mach number of 0.1 and a fuel-air ratio of 0.015. These tests showed that combustion was stable and ignition could be achieved with inlet air temperatures of 600° and 700° F (589 and 644 K) and with pressures as low as 0.5 atmosphere. Similarly, combustion was stable at a pressure of 1.0 atmosphere and inlet air temperatures as low as 150° F (339 K). However, reference Mach numbers as low as 0.06 were required to maintain stable combustion when both pressure and temperature were decreased to 0.5 atmosphere and 100° F (311 K).

INTRODUCTION

Advanced aircraft missions require turbojet engine combustors that are short, efficient, low in pressure loss, and capable of sustained performance at inlet air temperatures above 1000° F (811 K) and combustor exit temperatures above 2000° F (1366 K). In addition to obvious durability problems under such operating conditions, the require-ments of short length and low pressure loss impose severe mixing problems. Thus a satisfactory combustor exit temperature distribution may be very difficult to achieve.

The Lewis Research Center is engaged in research directed toward development of combustors suitable for advanced engines (ref. 1); included in this program are combustors composed of an array of swirl-can modules. Previous research on this type of combustor is reported in references 2 to 5. The present investigation evaluates the performance of a combustor composed of an array of swirl-can modules like those developed in the single-module studies reported in reference 5. Hence, the modules reported herein are of advanced design and are smaller in size than those previously investigated in combustor arrays. The tests were conducted using liquid fuel at combustor operating conditions simulating those encountered in advanced engine applications. Each swirl-can module consists of an inlet section which serves as a carburetor, followed by a swirler and a divergent conical combustor can. In operation, primary combustion air enters the carburetor and mixes with fuel. The fuel-air mixture passes through the swirler and burns in the combustor can. Secondary combustion air flows axially past the swirl-can module, recirculates in the wake, and completes the combustion reaction. The mixing of diluent air and combustion products occurs through recirculation and eddy diffusion.

Swirl-can combustor arrays offer the following advantages:

(1) Durability should be increased by having no diluent air entry ports in the combustor liner. The air entry ports produce stress concentration points which are frequently the source of liner failure.

(2) The combustor exit temperature profile can be adjusted by controlling the fuel flow to individual modules.

(3) Nozzle fouling problems, common at the high temperatures of interest here, are alleviated by the use of a low pressure fuel system with relatively large flow passages and control orifices located away from the combustion zone.

(4) Smoke formation is reduced by the premixing of fuel and air and by the abundance of air available at all stages of the burning process.

Swirl-can combustors have demonstrated good performance with gaseous fuels (ref. 2), vaporized liquid fuels (ref. 3), and liquid fuel (ref. 4). The combustor described in reference 4 consisted of a rectangular test section housing twenty-one 2.9-inch- (7.36-cm-) diameter swirl-can modules 8 inches (20.32 cm) long. The length from diffuser inlet to combustor exit was 39 inches (99.1 cm) and the liner height was 10.75 inches (27.3 cm). While this combustor produced generally satisfactory performance, the module size was too large for application to short length combustors and to combustors with smaller liner height. The purpose of the present investigation was to improve on the applicability of swirl-can combustors. A simplified, smaller swirl-can module design, previously described in reference 5, was used. For expediency the combustor housing was the same one used in reference 4. The reduction in swirl-can size permitted the use of a larger number of modules and allowed the modules to be entirely contained within the diffuser. These changes reduced the combustor length by 6 inches (15.24 cm).

APPARATUS

Facility

The closed-duct test facility is shown schematically in figure 1. The facility was connected to the laboratory air supply and exhaust systems. Remote control valves upstream of the test section regulated airflow and combustor pressure. Combustion air was passed through an indirect-fired heat exchanger capable of heating air to 600° F (589 K) to obtain required inlet air temperatures. Higher inlet air temperatures were obtained by using a direct-fired (vitiating) preheater which consisted of ten J71 combustor cans. Mixing baffles downstream of the J71 cans produced uniform temperature profiles at the combustor inlet.

Test Section

The test section shown in figure 2 was scaled to simulate a 90° sector of a full annulus turbojet engine combustor with a 57-inch (1.45-m) outer diameter. The test section was rectangular in cross section with a 12-inch (30.5-cm) height and a 30-inch (76.2-cm) width. The diffuser had an included angle of 33° and was 15 inches (38.1 cm) long. Five equally spaced splitter vanes were installed in the upstream end of the diffuser to improve the air velocity profile at the combustor inlet. The diffuser also contained the swirl-can module array which was positioned so module trailing edges coincided with the downstream edge of the diffuser. Arrays were mounted on the upper wall of the diffuser, on an access hatch, to permit easy access to the swirl-can modules without dismantling the rig. The diffuser was followed by a constant-area section 6 inches (15.24 cm) long and an exit ramp 12 inches (30.48 cm) long with a 5 inch (12.7 cm) combustor exit height. The overall length from the diffuser inlet to the combustor exit plane was 33 inches (84 cm). A film-cooled liner, extending from the downstream end of the swirl-can modules to the combustor exit plane, protected the housings. A photograph of the test installation is shown in figure 3.

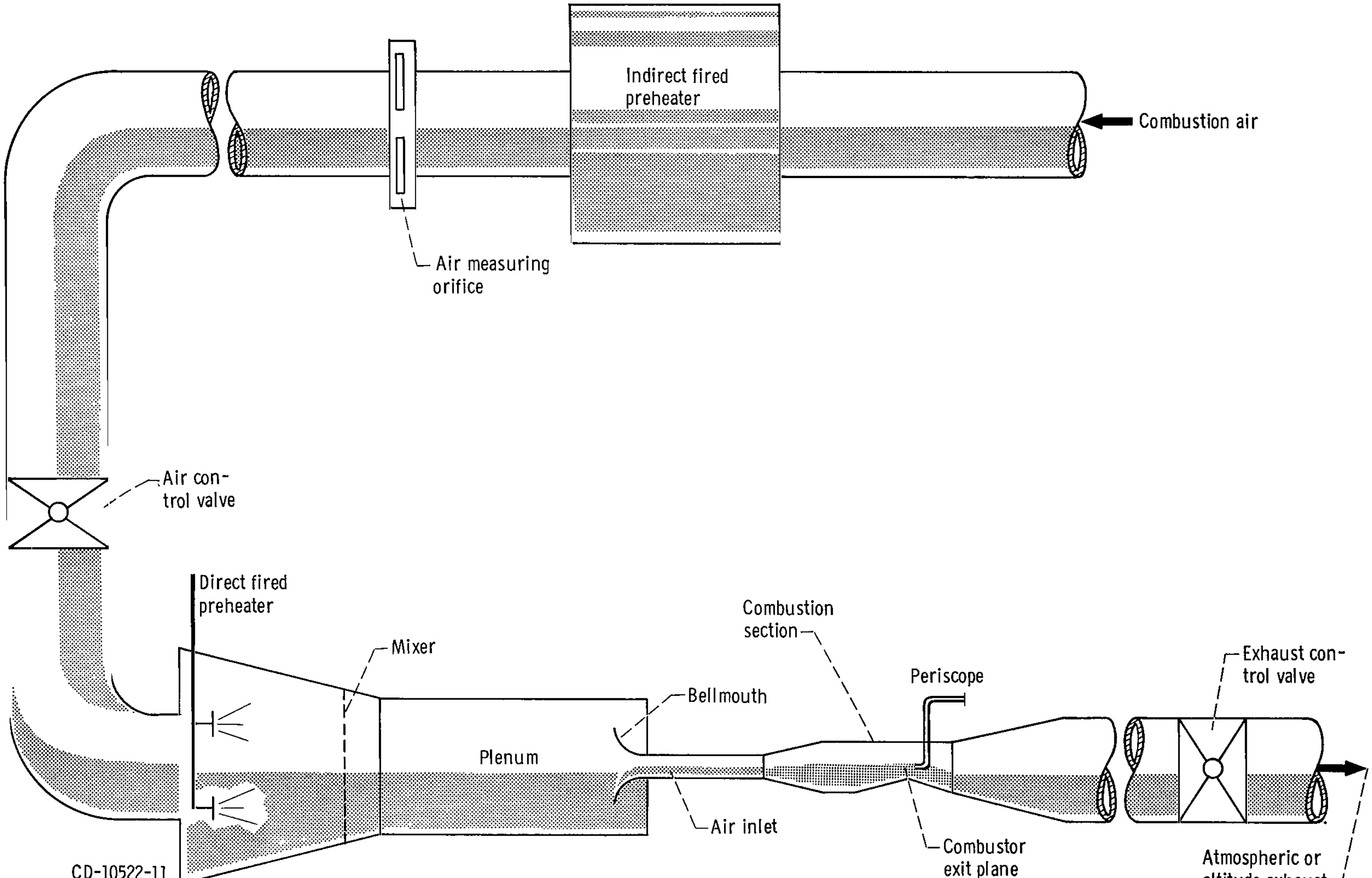


Figure 1. - Test facility. Combustor installation and auxiliary equipment.

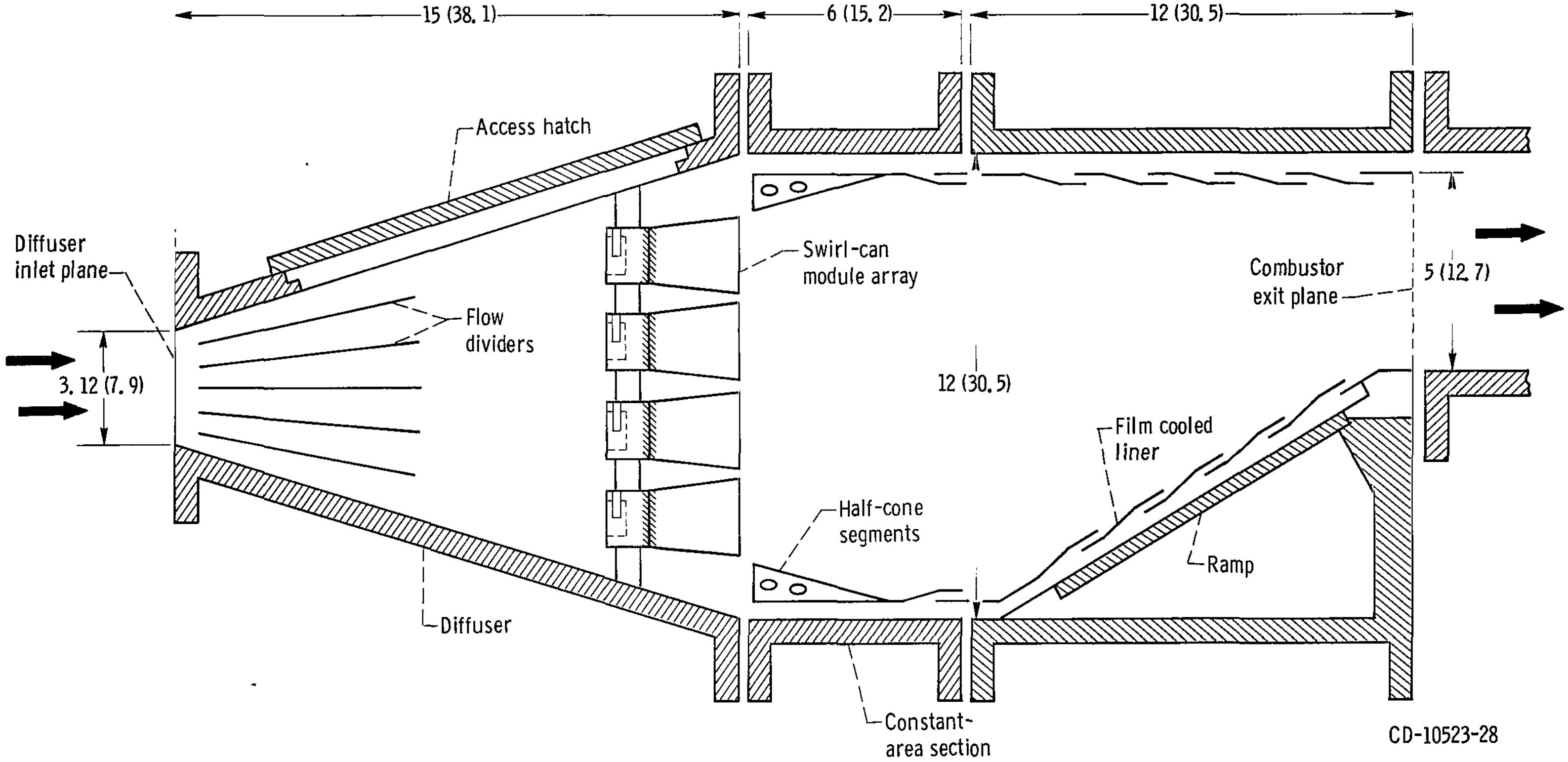


Figure 2. - Combustor installation in test section. Dimensions are in inches (cm).

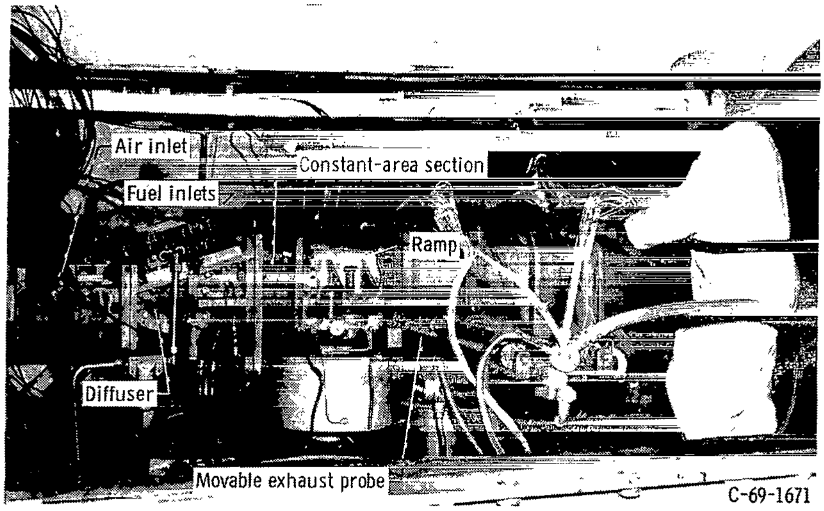


Figure 3. - Test installation.

Instrumentation

Air flow rates were measured by square-edged orifices installed according to ASME specifications. Fuel flows were measured by turbine-type flowmeters which were connected to frequency-to-voltage converters.

Locations of pertinent instrumentation planes and arrangements of pressure and temperature probes are shown in figure 4. Pressures in the inlet section were measured by five rakes, each consisting of five-point total pressure tubes, and by four wall static pressure taps (section A-A, fig. 4). Temperatures were measured by 10 chromel-alumel thermocouples (section B-B, fig. 4). Pressure distributions in the diffuser upstream of the swirl-can inlets were measured by six rakes, each consisting of five total pressure tubes and one stream static pressure tube (section C-C, fig. 4). Combustor exit total pressures and temperatures were recorded by a movable seven-point total pressure and seven-point total temperature rake (section D-D, fig. 4). The exhaust rake is shown in figure 5. The temperature probes were constructed of platinum - 13 percent rhodium platinum and were the high recovery aspirating type referred to as type 6 in reference 6. The thermocouples were also used to detect the presence of flame at the combustor exit plane. Significant fluctuations in thermocouple outputs occurred when flames were present. Four static pressure taps measured static pressure at the combustor exit. Temperature and pressure surveys at the combustor exit were made by traversing the probe horizontally across the exit nozzle at a speed which produced approximately one reading every 0.5 inch (1.27 cm). All pressures, with the exception of combustor exit total pressures, were measured and recorded by the Laboratory's Digital Automatic Multiple Pressure Recorder (DAMPR). Combustor exit total pressures were measured by strain-gage

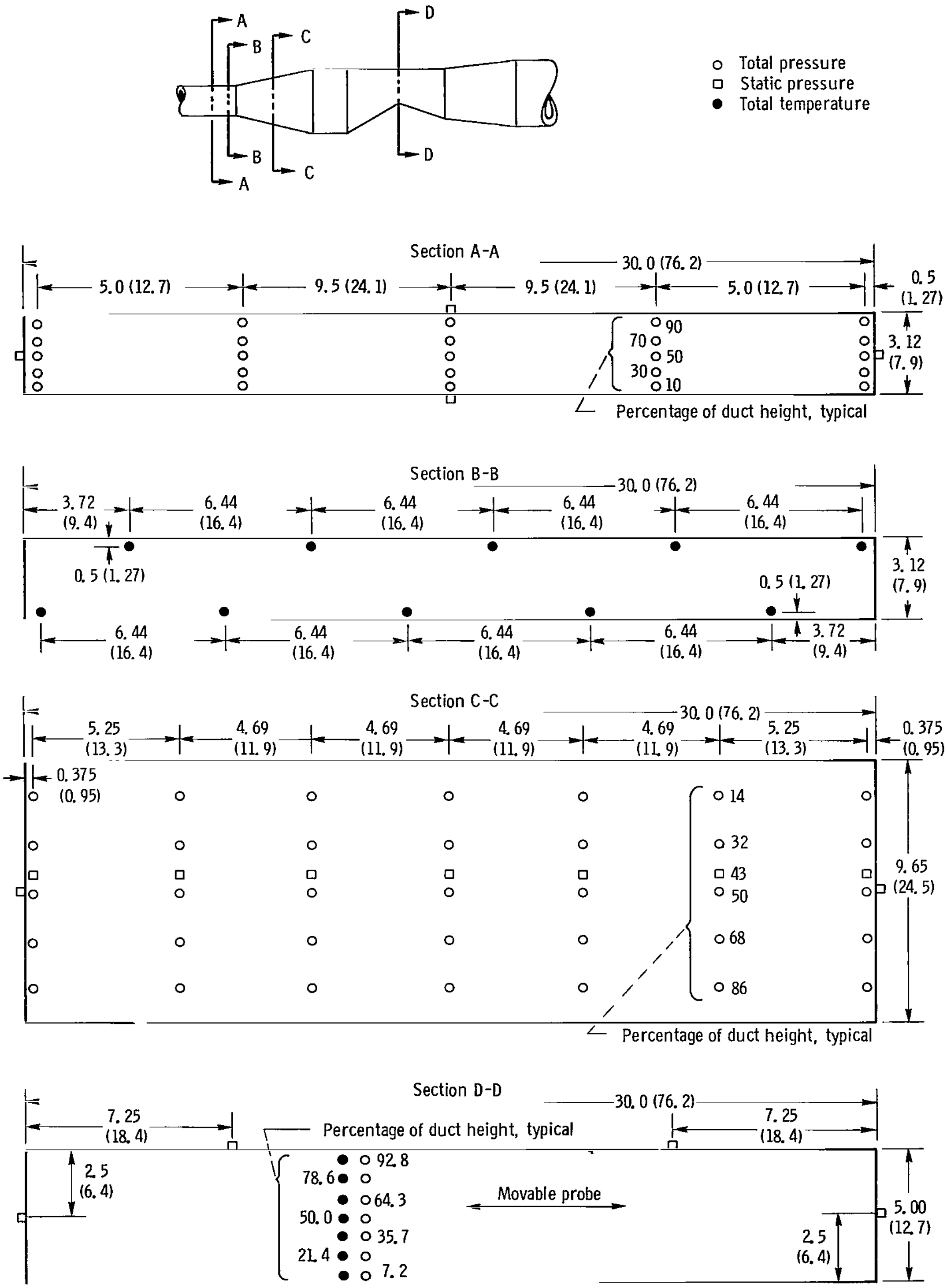


Figure 4. - Locations of pertinent instrumentation planes and locations of temperature and pressure probes in instrumentation planes (constant width, variable height). Dimensions are in inches (cm).

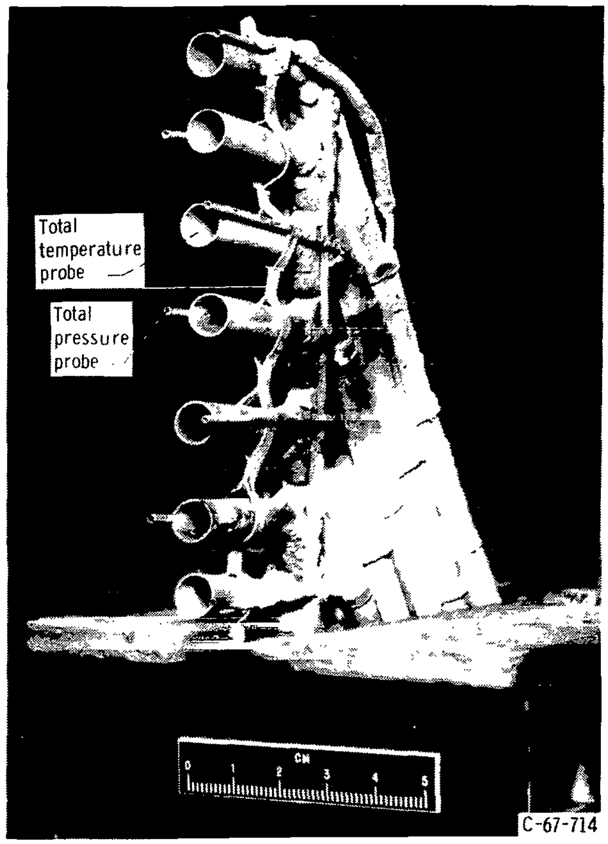


Figure 5. - Exhaust rake.

pressure transducers and were processed by the Laboratory's Central Automatic Data Processing System (ref. 7) which also processed thermocouple and fuel flowmeter outputs.

Data required to monitor the combustor, such as fuel and air flows, combustor pressures, and inlet and outlet air temperatures, were displayed in the control room. A periscope mounted downstream of the combustor exit plane provided a view of the swirl-can combustor modules.

Swirl-Can Combustor Modules

The swirl-can combustor module design used in this investigation was developed previously in a single module test facility and is described in reference 5. The modules consisted of three components: a carburetor section where fuel and air mixed, a swirler through which the mixture passed prior to combustion, and a diverging combustor can which served as a flameholder. A sketch of a swirl-can module is shown in figure 6. Fuel was supplied to each module through a 3/16-inch- (0.48-cm-) diameter tube positioned tangentially to the carburetor. A control orifice was installed in the fuel tube and located out-

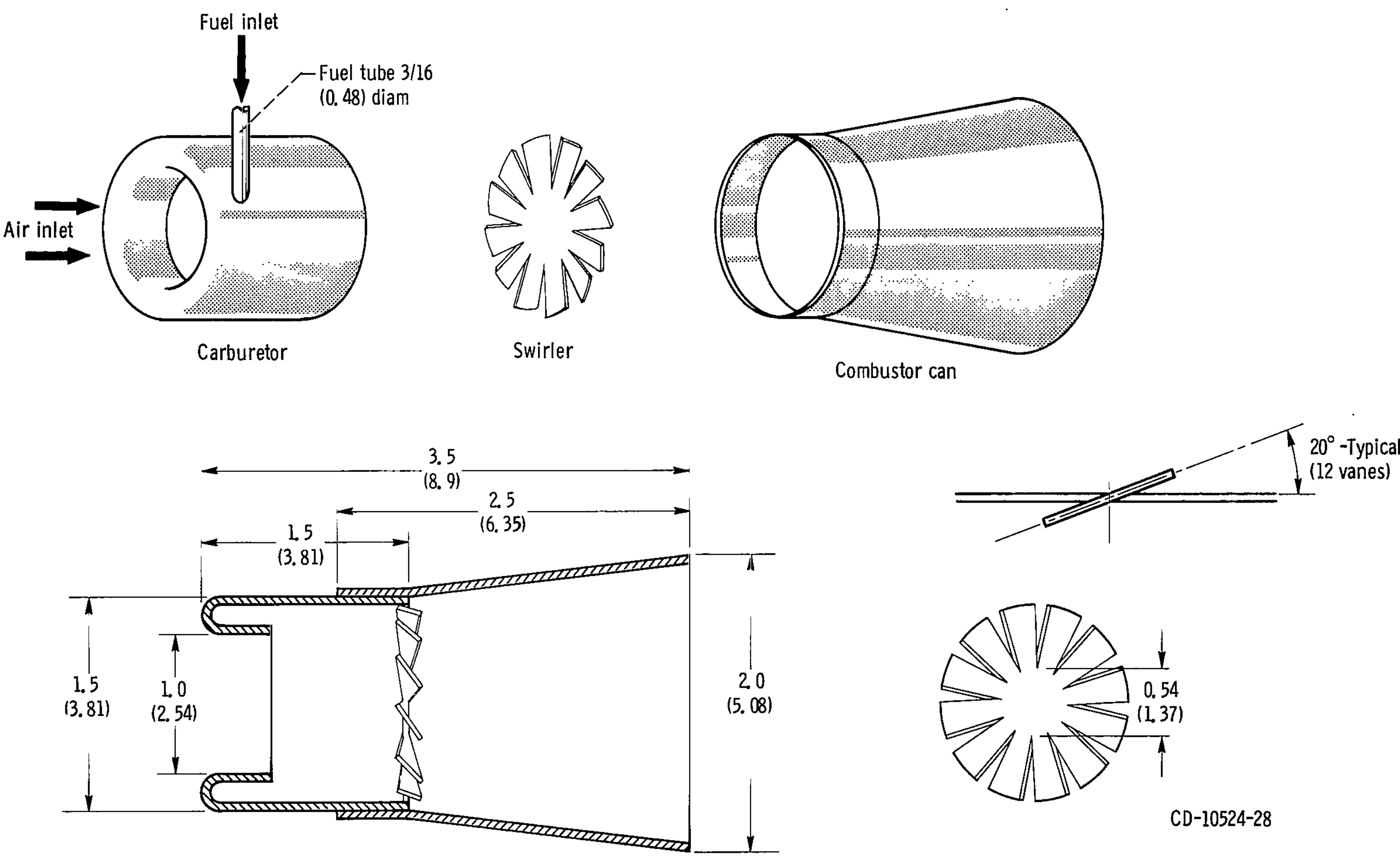
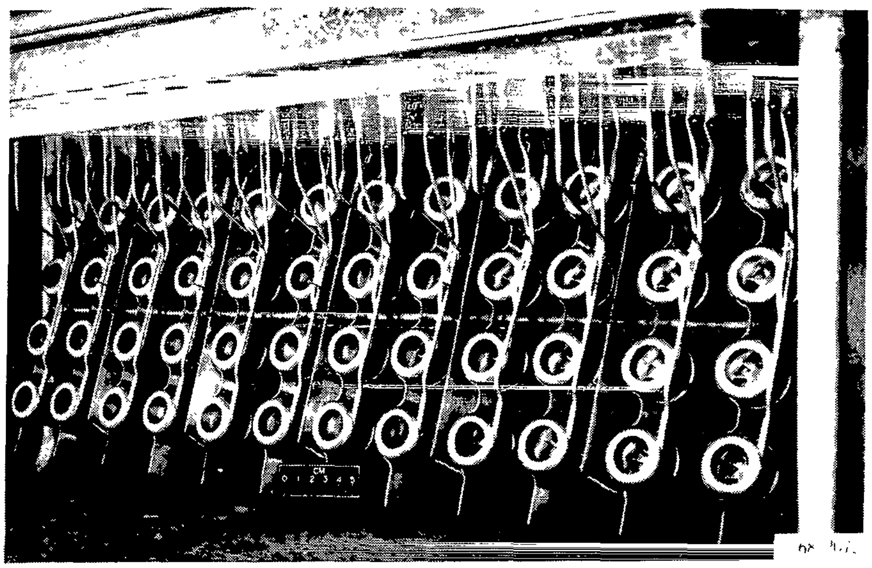


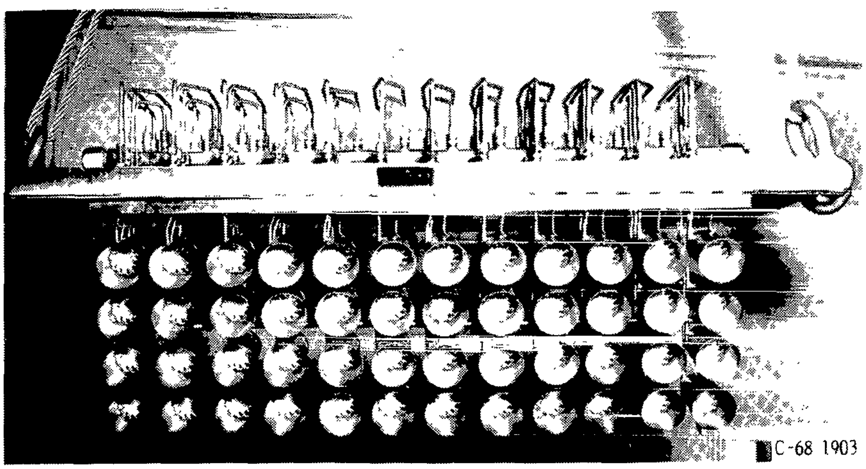
Figure 6. - Swirl-can combustor module. Dimensions are in inches (cm).

side the combustion chamber. A single carburetor design was used throughout. Airflow through the carburetor was controlled by the open flow area between swirler vanes.

Forty-eight swirl-can combustor modules comprised each combustor array. The swirl-can modules were positioned in four horizontal rows of twelve each. The combustor array is shown in figures 7(a) (view looking downstream) and 7(b) (view looking upstream). Numerous modifications of this array were made to improve combustor exit temperature distribution and reduce flame length. These modifications consisted of varying the amount of fuel to the four swirl-can rows and varying swirler open area by changing the vane angle. Additional modifications, consisting of attachments to the swirl-can modules and to the combustor liners, are discussed in a subsequent section.



(a) View looking downstream.



(b) View looking upstream.

Figure 7. - Swirl-can combustor module array installation on diffuser hatch.

RESULTS AND DISCUSSION

Tests were conducted over a range of fuel-air ratios at the combustor test conditions given in table I. Fuel to air ratios for each test were increased until an average combustor exit temperature of 2200° F (1478 K) was attained or until a maximum local temperature exceeded 2700° F (1756 K). A jet type fuel conforming to ASTM-A1 specifications was used for all tests. This fuel had an average hydrogen-carbon ratio of 0.161 and a lower heating value of 18 600 Btu per pound (43 300 J/g). A capacitor-discharge type ignition system with a maximum energy of 20 joules ignited the combustors.

TABLE I. - COMBUSTOR TEST CONDITIONS

[Combustor inlet pressure, 3 atm.]

Test condition	Combustor inlet temperature		Combustor inlet Mach number	Combustor reference velocity[a]		Combustor reference Mach number[a]
	$^{\circ}$F	K		ft/sec	m/sec	
1	600	589	0.241	100	30.5	0.0627
2	1150	894	.293	150	45.7	.0763
3	600	589	.144	60	18.3	.0376
4	↓	↓	.313	130	39.6	.0815
5	↓	↓	.361	150	45.7	.0940
6	↓	↓	.433	180	54.9	.1128
7	1150	894	.195	100	30.5	.0509
8	1150	894	.352	180	54.9	.0916

[a]Based on maximum cross-sectional area of combustor housing and total pressure and temperature at diffuser inlet.

Combustor Development

Combustor modifications were evaluated by comparing combustion efficiency, pressure loss, and combustor exit temperature distribution. Combustion efficiencies of all of the combustor modifications evaluated proved to be near 100 percent with pressures of 3 atmospheres, inlet air temperatures of 600° and 1150° (589 and 894 K), reference velocities up to 150 feet per second (45.7 m/sec), and fuel to air ratios of 0.015 or higher. Thus, combustion efficiency could be used as a critical parameter only at fuel-air ratios below 0.015 and reference velocities above 150 feet per second (45.7 m/sec). Pressure drop increased substantially for modifications with increased blockage. Blockage was

TABLE II. - COMBUSTOR MODIFICATIONS

Model	Swirler open area		Fuel distribution to swirl-can module rows	Figure showing modification	Description of modification	Result of modification
	in.^{2}	cm^2				
1	0.4	2.58	Uniform	7	Basic 48 swirl-can module array	Poor performance with hot zones in center of combustor exit plane
2	0.4	2.58	Uniform	------	Basic array with 1 in. (2.54 cm) high blockage strips attached to upper and lower liners of constant-area section	Slight improvement in performance but temperature peaks and long flames still produced
3A 3B	0.4 .6	2.58 3.87	Uniform Uniform	8 8	Basic array with half-cone segments attached to upper and lower liners of constant-area section (cones positioned between swirl-can modules; each segment had five 1/2 in. (1.27 cm) diameter diluent air holes)	Substantial improvement in radial exit profile and pattern factor which was 0.34 to 0.40; long flame lengths still produced
4A 4B $4B_2$	0.4 .6 .6	2.58 3.87 3.87	Uniform Uniform Nonuniform (1.5 times more fuel supplied to top and bottom swirl-can rows)	9	Basic array with air scoops attached to upper and lower liners of constant-area section	No appreciable improvement in performance; long flame lengths and poor pattern factors; redistributing fuel flow improved performance but showed no advantage over model 3 designs; testing with scoops terminated
5A 5B	0.4 .6	2.58 3.87	Nonuniform (1.5 times more fuel supplied to top and bottom swirl-can rows)	10	Model 3 with crosses installed in array between swirl-can modules	Improvement in combustion performance but increased pressure loss; flame length reduced and circumferential exit profile significantly improved
6A 6B 6C	0.4 .6 .2	2.58 3.87 1.29	Nonuniform (1.5 times more fuel supplied to top and bottom swirl-can rows)	11	Model 5 with 1/4 in. (0.64 cm) and/or 1/8 in. (0.32 cm) wide fuel distribution rings installed in combustor cans of swirl-can modules	Fuel distribution improved and flame lengths substantially reduced; pattern factors, 0.26 to 0.30
7A 7B 7C	0.4 .6 .2	2.58 3.87 1.29	Nonuniform (1.5 times more fuel supplied to top and bottom swirl-can rows)	2, 8, 11	Model 6 (half-cone segments, crosses, fuel distribution rings) with all diluent holes blocked on half-cone segments	Best performance achieved especially with smallest swirler open area; pattern factors, 0.20 to 0.30 with 600° F (589 K) inlet air temperature and 0.19 to 0.22 with 1150° F (894 K)

increased to improve combustor exit temperature distribution. Since even the highest pressure drops measured were comparable to current turbojet combustors and since combustion efficiencies were high at the design points, combustor exit temperature distribution became the main criterion by which performance was judged.

A list of the more important combustor modifications investigated is given in table II. The numerical designation for each modification (1 to 7) indicates the sequential order in which they were evaluated. The alphabetical designations A, B, and C indicate the swirler open area for each model: (A) models had swirler open areas of 0.4 square inch (2.58 cm^2); (B) models had swirler open areas of 0.6 square inch (3.87 cm^2); and (C) models had swirler open areas of 0.2 square inch (1.29 cm^2). Subscripts indicate additional minor modifications such as supplying varying amounts of fuel to the 4 swirl-can rows.

The basic array with no modifications, model 1, shown in figures 7(a) and (b) produced poor results. Radial average temperature distributions at the combustor exit showed hot center zones with cold zones along the top and bottom liners. Flames were long and yellow and extended into the combustor exit plane. Pressure instrumentation in the diffuser showed that most of the airflow was concentrated along the diffuser top and bottom walls with reduced airflow in the center of the array. Pattern factor was near 1.0. In the combustor exit plane, hot spots were observed in the swirl-cans wakes.

Placing 1 inch (2.54 cm) high blockage strips at the diffuser exit along the top and bottom liners (model 2) improved radial temperature distributions but still produced temperature peaks and long flames. Pattern factors were still high - from 0.6 to 0.8.

The model 3 modification in which half-cone segments with diluent air holes were placed along the top and bottom of the constant area section substantially improved performance. The improvement was especially evident with the larger swirler open area (model 3B). Figure 8 shows the positioning of half-cone segments between swirl-cans and their installation on the top and bottom liners of the constant-area section. Eleven half-cone segments were attached to each liner. Model 3 modifications improved average radial temperature profiles at the combustor exit and reduced pattern factor to 0.34 to 0.40 for 600° F (589 K) inlet temperature. However, long flame lengths were still produced with this modification and locations of swirl-can modules could be determined by hot spots at the combustor exit.

Placing air deflector scoops on the top and bottom liners of the constant-area section (model 4) did not appreciably improve performance. These scoops are shown in figure 9. They were positioned across the top and bottom liners of the constant-area section. Air deflected by the scoops did not penetrate into the combustor but rather washed along the liners and produced poor radial profiles. Increasing fuel flow to the inner and outer rows of modules so that they received more fuel than the center rows improved radial exit profiles but showed no advantage over model 3 designs. Testing with air scoops was therefore terminated and the half-cone segments were installed on the constant-area section

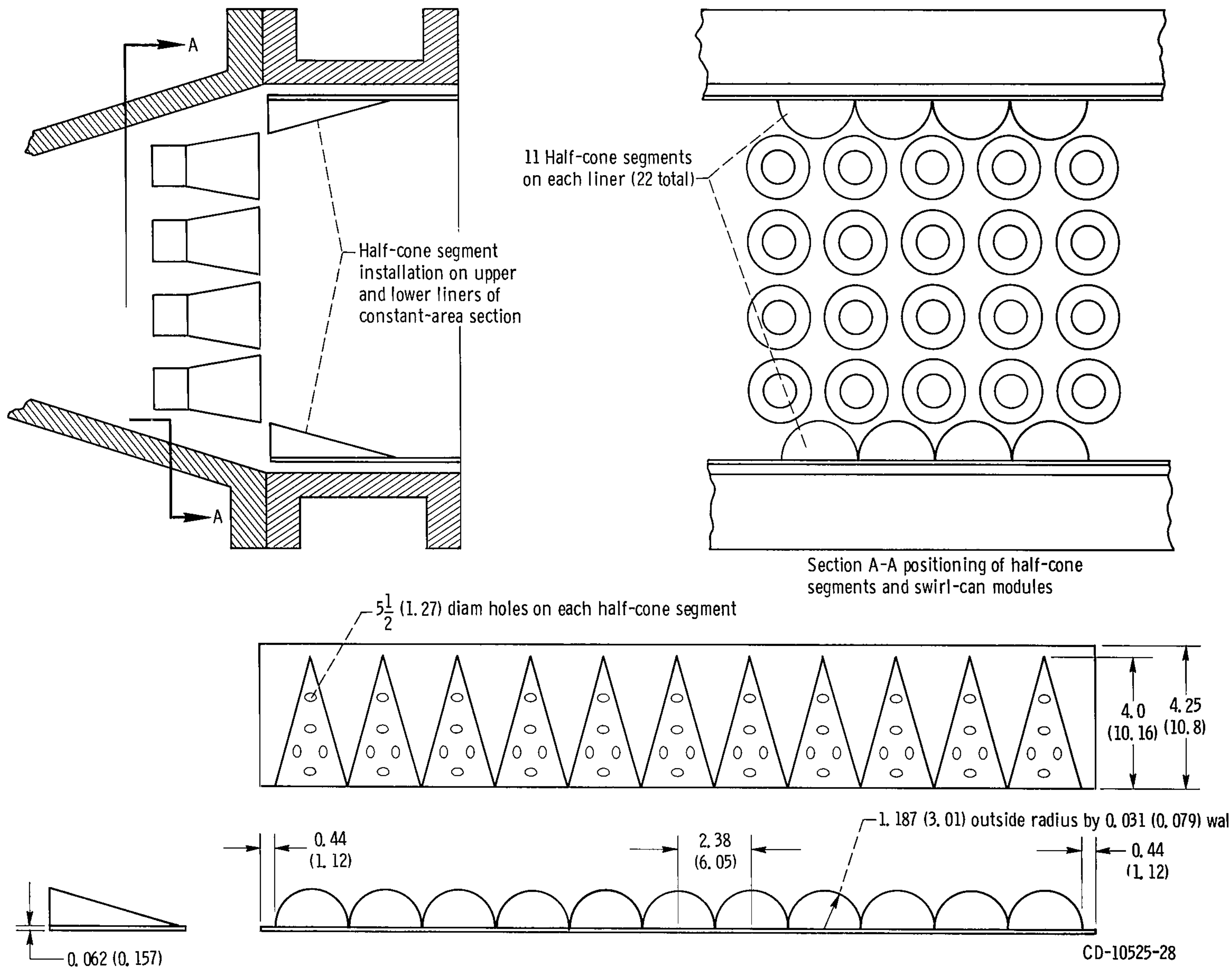


Figure 8. - Installation and positioning of half-cone segments. Dimensions are in inches (cm).

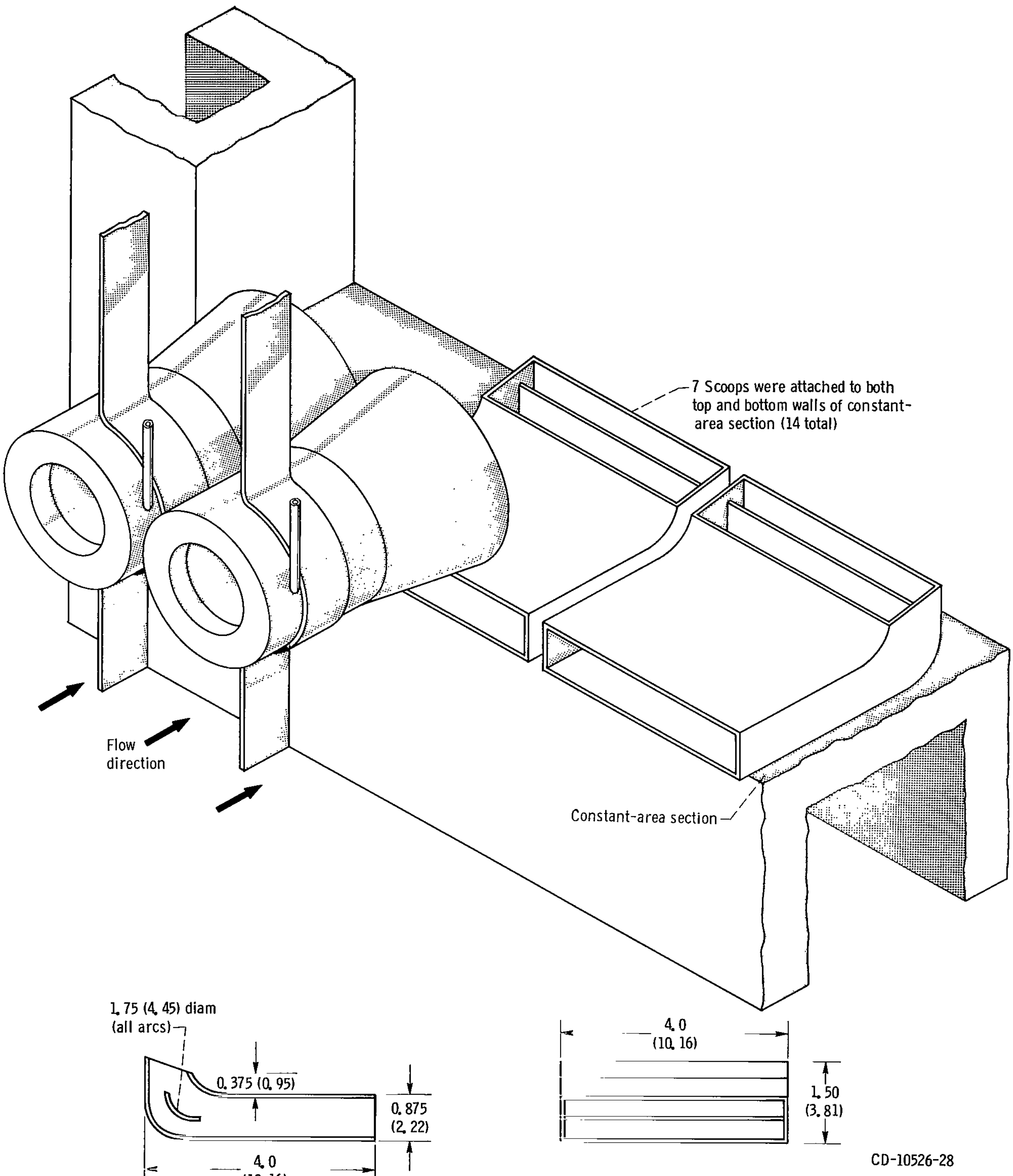


Figure 9. - Air deflector scoops for the model 4 combustor configuration. Dimensions are in inches (cm).

liners for all subsequent tests. Subsequent tests also proportioned fuel to the 4 swirl-can rows. Best results were achieved when the outer swirl-can rows recieved 1.5 times the fuel flow of the center rows.

Model 5 incorporated 3/8 inch (0.94 cm) wide crosses between all of the swirl-cans in the array (fig. 10). The crosses substantially improved performance but increased the pressure loss. Combustor exit temperatures showed that hot spots which had formerly occurred in the wake of swirl-can modules were eliminated. The hot gas from each swirl-can blended with that of the other modules and produced a flat circumferential temperature profile. The presence of flame at the combustor exit plane could be detected only at the highest fuel-air ratios with 600° F (589 K) temperatures and could not be detected with 1150° F (589 K) temperatures. Pattern factors were reduced to 0.30 to 0.35. However, the increased blockage caused by the crosses deflected air to the top and bottom of the combustor and produced poor radial exit temperature profiles.

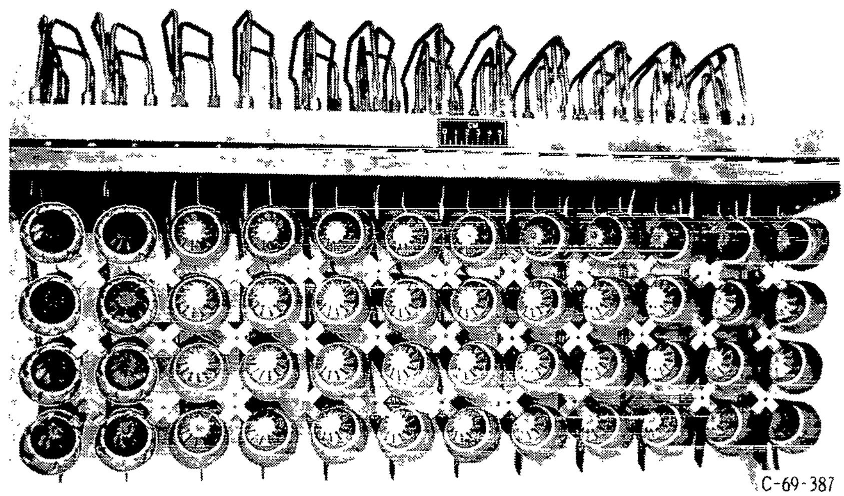


Figure 10. - Combustor array with crosses between swirl-can combustor modules and with fuel distribution rings mounted in combustor can. View looking downstream.

Combustion intensity was significantly increased by the model 6 modification which placed fuel distribution rings in the combustor cans 1 inch (2.54 cm) upstream of their trailing edges as shown in figure 11. Effects of fuel distribution rings on swirl-can performance were studied previously and are described in reference 5. It appears that the rings prevented fuel from flowing along the wall of the combustor can. The present study investigated both 1/4 and 1/8 inch (0.64 and 0.32 cm) wide rings. Both sizes improved fuel distribution. Model 6 combustors had short, bluish, and often transparent flames. No indication of flame at the combustor exit plane was observed. Pattern factors were further reduced to about 0.26 to 0.30. Radial combustor exit temperature profiles were still somewhat distorted with cold spots along top and bottom liners.

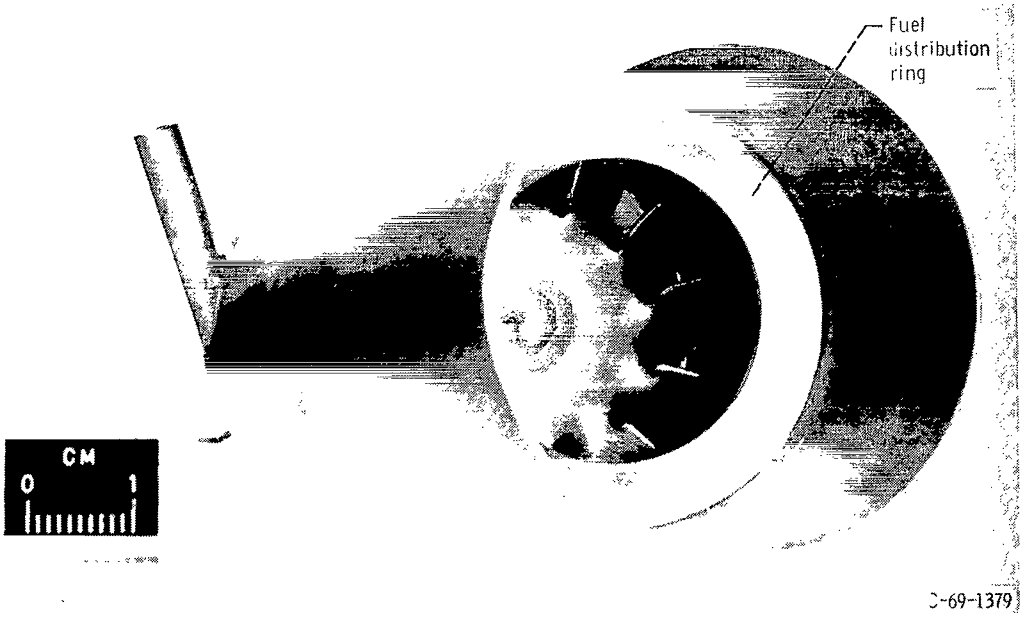


Figure 11. - Swirl-can module showing location of fuel distribution ring.

The diluent holes on the half-cone segments were sealed to improve combustor exit radial temperature profiles. This modification, model 7, also included the fuel distribution rings, crosses between swirl-can modules, and fuel orifices selected so that the inner and outer rows of modules received 1.5 times the fuel of the center rows. Model 7 combustors produced the best combustion performance. However, the highest pressure drop also resulted. Flames were short and blue, and burning extended uniformly across the combustor. Pattern factors were reduced to 0.20 to 0.30 for 600° F (589 K) inlet temperature and 0.19 to 0.22 for 1150° F (894 K) inlet temperature. Three model 7 combustors with different swirler open areas were investigated. The smallest swirler open area (model 7C) produced the best performance over the widest span of fuel to air ratios, and was therefore the one most extensively evaluated. The data presented in table III were obtained with model 7C. Combustion efficiency data for models 7A and 7B are also presented in table IV for comparison purposes.

Results indicated that half-cone segments, crosses between swirl-can modules, fuel distribution rings, fuel proportionating, and proper swirler open areas were all important for good combustor performance. The half-cone segments provided uniform blockage along the liner walls. Crosses eliminated cold spots between swirl-cans and hot spots in the wakes of swirl-cans, thus producing uniform circumferential combustor exit temperature profiles. Fuel distribution rings increased combustion intensity by better distributing fuel and reducing flame length. Fuel proportionating to the 4 swirl-can rows compensated for nonuniform airflow distributions in the diffuser.

TABLE III. - COMBUSTOR PERFORMANCE RESULTS FOR MODEL 7C

(a) Combustion tests; pressure, 3 atm

Run	Inlet air temperature		Air flow		Inlet Mach number	Nominal reference velocity		Fuel-air ratio	Average combustor outlet temperature		Combustion efficiency, percent	Combustor pressure loss, $\Delta P/P$, percent	Temperature distribution parameters		Pattern factor
	°F	K	lb/sec	kg/sec		ft/sec	m/sec		°F	K			δ_{stator}	ε_{rotor}	
1	592	584	17.50	7.94	0.146	60	18.3	------	----	----	---	2.00	-----	-----	----
2	583	578	16.93	7.68	.146			0.0084	1129	882	93	2.07	0.161	0.021	1.21
3	583	578	17.01	7.72	.148			.0104	1273	962	99	2.13	.203	.094	1.23
4	586	581	17.49	7.93	.145			.0122	1425	1046	102	2.15	.233	.044	1.26
5	592	584	17.42	7.90	.148			.0146	1614	1151	102	2.16	.199	.023	1.22
6	590	582	17.02	7.72	.147			.0178	1775	1241	102	2.22	.236	.023	1.25
7	587	581	17.45	7.92	.148			.0204	1932	1328	102	2.23	.310	.023	1.32
8	586	581	17.41	7.90	.147			.0224	2069	1404	104	2.23	.286	.042	1.30
9	596	586	28.90	13.11	.259	100	30.5	------	----	----	---	5.78	-----	-----	----
10	595	586	29.45	13.36	.25			.0097	1238	943	97	6.19	.283	.073	1.28
11	531	550	29.30	13.29	.243			.0101	1208	926	98.5	5.41	.384	.133	1.28
12	531	550	28.70	13.02	.239			.0118	1332	995	102	5.40	.329	.125	1.29
13	595	586	29.49	13.38	.259			.0124	1449	1090	102	6.49	.242	.062	1.26
14	527	548	28.60	12.97	.244			.0141	1489	1082	104	5.42	.265	.108	1.28
15	595	586	29.86	13.54	.263			.0146	1615	1152	105	6.63	.252	.027	1.27
16	577	576	29.74	13.49	.246			.0156	1657	1175	105	5.91	.376	.011	1.23
17	597	581	29.52	13.39	.259			.0176	1781	1245	104	6.49	.341	.039	1.28
18	596	586	29.96	13.59	.264			.0192	1899	1309	105	6.51	.296	.048	1.30
19	596	586	29.94	13.58	.262			.0194	1911	1317	105	6.51	.259	.063	1.27
20	536	553	28.80	13.06	.247			.0210	1932	1328	105	5.58	.244	.095	1.25

21	595	586	30.01	13.61	0.260	100	30.5	0.0217	2060	1400	106	6.31	0.254	0.070	1.27
22	595	586	29.67	13.46	.267	100	30.5	.0220	2004	1369	104	6.61	.272	.060	1.26
23	597	587	29.54	13.40	.260	100	30.5	.0232	2092	1421	103	6.61	.226	.082	1.24
24	595	586	36.00	16.32	.328	130	39.6	------	----	----	---	8.92	-----	-----	----
25	594	585	36.82	16.70	.326			.0099	1221	933	93	9.67	.344	.121	1.31
26	594	585	36.72	16.65	.329			.0125	1448	1082	102	10.10	.263	.060	1.29
27	596	586	36.77	16.67	.332			.0150	1607	1148	102	10.56	.268	.051	1.28
28	595	586	36.68	16.63	.332			.0151	1623	1157	103	10.19	.316	.031	1.33
29	594	585	36.38	16.50	.328			.0174	1748	1226	102	10.48	.335	.042	1.35
30	593	584	36.43	16.52	.326			.0175	1752	1228	102	10.18	.287	.019	1.30
31	596	586	36.89	16.73	.326			.0196	1906	1314	104	10.13	.327	.037	1.34
32	593	584	36.45	16.53	.325			.0225	2048	1393	102	10.27	.333	.053	1.34
33	594	585	43.81	19.87	.412	150	45.7	------	----	----	---	14.03	-----	-----	----
34	595	586	43.63	19.79	.406			.0099	1118	876	78	15.03	.509	.277	1.48
35	594	585	43.59	19.77	.411			.0126	1405	1036	96	15.74	.329	.081	1.35
36	596	586	43.62	19.78	.409			.0150	1582	1134	100	15.44	.322	.054	1.34
37	596	586	43.83	19.88	.410			.0177	1750	1227	102	15.76	.330	.042	1.34
38	596	586	43.60	19.77	.408			.0200	1896	1308	101	15.80	.329	.058	1.34
39	594	585	44.89	20.36	.406			.0223	2032	1384	101	15.88	.319	.070	1.33
40	598	587	50.66	22.97	.500	180	54.9	------	----	----	---	19.40	-----	-----	----
41	595	586	50.58	22.94	.500			.0160	1001	811	60	20.45	.763	.308	1.70
42	596	586	50.68	22.98	.502			.0125	1270	961	81	21.01	.615	.156	1.64
43	589	582	50.84	23.06	.4971			.0150	1451	1061	85	22.10	.535	.211	1.55
44	591	583	50.73	23.01	.500			.0175	1642	1167	92	21.73	.411	.090	1.46
45	593	584	50.63	22.96	.494			.0201	1821	1267	95	21.80	.428	.077	1.45
46	595	586	50.86	23.07	.501			.021	1910	1316	95.4	21.97	.389	.075	1.41
47	1149	894	23.07	10.46	.255	120	36.58	------	----	----	---	4.79	-----	-----	----
48	1150	894	23.58	10.70	.247			.0094	1743	1224	102	5.16	.276	.054	1.25
49	1149	894	22.86	10.37	.257			.0116	1855	1286	100	5.18	.236	.054	1.22
50	1153	896	22.90	10.39	.252			.0145	2002	1367	98	5.27	.211	.055	1.21

TABLE III. - Continued. COMBUSTOR PERFORMANCE RESULTS FOR MODEL 7C

(a) Concluded. Combustion tests; pressure, 3 atm

Run	Inlet air temperature		Air flow		Inlet Mach number	Nominal reference velocity		Fuel-air ratio	Average combustor outlet temperature		Combustion efficiency, percent	Combustor pressure loss, $\Delta P/P$, percent	Temperature distribution parameters		Pattern factor
	^{o}F	K	lb/sec	kg/sec		ft/sec	m/sec		^{o}F	K			δ_{stator}	δ_{rotor}	
51	1152	895	22.48	10.20	0.250	120	36.58	0.0165	2125	1438	99	5.27	0.218	0.055	1.21
52	1153	896	23.10	10.48	.252	120	36.58	.0174	2203	1479	102	5.31	.225	.058	1.21
53	1152	895	23.12	10.49	.251	120	36.58	.0174	2206	1481	102	5.32	.215	.056	1.20
54	1150	894	28.52	12.94	.317	150	45.72	------	----	----	---	7.70	-----	-----	----
55	1169	894	28.52	12.98	.331			------	----	----	---	8.17	-----	-----	----
56	1149	894	28.54	12.95	.321			.0097	1762	1234	100	8.28	.241	.062	1.22
57	1148	893	28.64	12.99	.321			.0114	1852	1284	101	8.30	.223	.059	1.21
58	1153	896	28.87	13.10	.326			.0136	1957	1342	100	8.61	.183	.054	1.19
59	1149	894	28.40	12.88	.317			.0156	2070	1405	99	8.44	.197	.054	1.19
60	1150	894	29.20	13.25	.322			.0166	2162	1456	102	8.42	.189	.059	1.19
61	1149	894	28.78	13.05	.317			.0176	2194	1474	100	8.44	.203	.058	1.19
62	1151	895	28.78	13.05	.318			.0185	2261	1511	102	8.60	.199	.054	1.19
63	1136	886	34.90	15.83	.397	180	54.86	------	----	----	---	11.72	-----	-----	----
64	1131	884	34.95	15.85	.399			.0098	1747	1226	101	12.52	.289	.030	1.27
65	1131	884	34.50	15.65	.404			.0116	1834	1274	99	12.98	.232	.058	1.21
66	1127	881	34.52	15.66	.397			.0129	1922	1323	101	12.93	.258	.052	1.24
67	1128	882	34.61	15.70	.398			.0147	2029	1382	101	13.06	.245	.047	1.23
68	1128	882	35.28	16.00	.402			.0157	2110	1427	102	13.15	.262	.036	1.25
69	1131	884	34.76	15.77	.396			.0175	2197	1476	102	13.20	.271	.035	1.26

(b) Smoke tests; combustor pressure, 3 atm; air flow, 28.6 lb/sec (12.97 kg/sec); ΔP across paper, 5 psi (2.27 N/m^2); and sample flow, 0.6 ft^3/min (283.2 cm^3/sec).

Run	Inlet air temperature		Nominal reference velocity		Fuel-air ratio	Proposed smoke number
	^{o}F	K	ft/sec	m/sec		
Tape travel, 4 in./min (0.169 cm/sec); filtering concentration, 0.3 $ft^3/in.^2$ (21.94 cm^3/cm^2)						
1	600	589	100	30.5	0.015	0
2	600	589	100	30.5	.02	
3	600	589	100	30.5	.022	
4	400	477	81	24.7	.022	
5	300	422	72	21.9	.024	
6	200	366	62	18.9	.024	
7	150	339	57	17.4	.024	

Run	Inlet air temperature		Nominal reference velocity		Fuel-air ratio	Proposed smoke number
	^{o}F	K	ft/sec	m/sec		
No tape travel; filtering concentration, 14.4 $ft^3/in.^2$ (1053 cm^3/cm^2); tape exposed to sample for 3 minutes						
1	600	589	100	30.5	0.015	0
2	600	589	100	30.5	.020	
3	600	589	100	30.5	.022	
4	400	477	81	24.7	.022	
5	300	422	72	21.9	.024	2.2
6	200	366	62	18.9	.024	11
7	150	339	57	17.4	.024	13

TABLE III. - Continued. COMBUSTOR PERFORMANCE RESULTS FOR MODEL 7C

(c) Blowout and altitude relight tests; fuel to air ratio, 0.015

Run	Inlet air temperature		Inlet air pressure (absolute), atm	Air flow		Reference Mach number	Performance description
	°F	K		lb/sec	kg/sec		
1	700	644	3.06	43.6	19.8	0.1	Ignition and stable combustion
2			2.72	38.8	17.6		
3			2.38	34.0	15.4		
4			2.04	29.1	13.2		
5			1.70	24.2	11.0		
6			1.53	21.8	9.9		
7			1.36	19.3	8.8		
8			1.02	14.5	6.6		
9			.85	12.0	5.4		
10			.68	9.7	4.4		
11			.50	7.3	3.3		
12	600	589	3.06	46.0	20.9		
13			2.72	41.0	18.6		
14			2.38	35.8	16.2		
15			2.04	30.6	13.9		
16			1.70	25.6	11.6		
17			1.36	20.4	9.3		
18			1.19	18.2	8.3		
19			1.02	15.4	7.0		
20			.85	12.5	5.9		
21			.68	10.2	4.6		
22			.50	7.7	3.5		

23	500	533	3.06	48.0	21.8	0.1	Ignition and stable combustion
24			2.72	42.6	19.3		
25			2.38	37.3	16.9		
26			2.04	32.0	14.5		
27			1.70	26.6	12.1		
28			1.36	21.3	9.7		
29			1.11	19.1	8.7		
30			1.02	16.1	7.3		
31			.85	12.9	5.9		
32			.68	10.7	4.9		
33			.50	8.0	3.6		Blowout (majority of swirl-can modules)
34			.50	6.6	3.0	.083	Ignition and stable combustion
35	400	477	3.06	52.9	24.0	.1	
36			2.72	47.0	21.3		
37			2.38	41.2	18.7		
38			2.04	35.3	16.0		
39			1.70	29.4	13.3		
40			1.36	23.5	10.7		
41			1.19	20.6	9.3		
42			1.02	17.6	8.0		
43			.85	14.7	6.7		No ignition, stable combustion
44			.68	11.8	5.4		Blowout (majority of swirl-can modules)
45			.68	9.8	4.5	.087	Ignition and stable combustion
46			.50	7.4	3.4	.087	No ignition, stable combustion

TABLE III. - Concluded. COMBUSTOR PERFORMANCE RESULTS FOR MODEL 7C

(c) Concluded. Blowout and altitude relight tests; fuel to air ratio, 0.015

Run	Inlet air temperature		Inlet air pressure (absolute), atm	Air flow		Reference Mach number	Performance description
	^{o}F	K		lb/sec	kg/sec		
47	300	422	3.06	53.9	24.4	0.1	Ignition and stable combustion
48			2.72	47.9	21.7		
49			2.38	41.9	19.0		
50			2.04	35.9	16.3		
51			1.70	29.9	13.6		
52			1.36	24.0	10.9		
53			1.19	21.0	9.5		
54			1.02	18.0	8.2		
55			.85	15.0	6.8		No ignition, stable combustion
56			.68	12.8	5.8		Blowout (majority of swirl-can modules)
57			.68	9.6	4.4	.075	Ignition and stable combustion
58			.50	6.6	3.0	.075	
59	250	394	3.06	55.8	25.3	.1	
60			2.72	49.6	22.5		
61			2.38	43.4	19.7		
62			2.04	37.2	16.9		
63			1.70	31.0	14.1		
64			1.36	24.8	11.2		
65			1.02	18.6	8.4		No ignition, stable combustion
66			.085	15.5	7.0		Blowout (majority of swirl-can modules)
67			.085	11.9	5.4	.077	No ignition, stable combustion
68			.068	9.5	4.3	.077	No ignition, stable combustion
69			.050	7.8	3.5	.077	No ignition, stable combustion

70	200	366	3.06	57.5	26.1	0.1	Ignition and stable combustion
71			2.72	51.1	23.8		
72			2.38	44.7	20.3		
73			2.04	38.3	17.4		
74			1.70	31.9	14.5		
75			1.53	28.8	13.1		No ignition, stable combustion
76			1.36	25.5	11.6		No ignition, stable combustion
77			1.02	19.2	8.7		No ignition, stable combustion
78			.085	16.0	7.3		Blowout (majority of swirl-can modules)
79			.085	12.8	5.8	.08	No ignition, stable combustion
80			.068	10.2	4.6	.08	Blowout (majority of swirl-can modules)
81			.068	7.7	3.5	.06	No ignition, stable combustion
82	150	339	2.38	46.8	21.2	.1	
83			2.04	40.1	18.2		
84			1.36	26.7	12.1		
85			1.02	20.1	9.4		
86			1.70	27.6	12.5	.083	
87			1.36	22.1	10.0	.083	
88	100	311	2.38	52.7	23.9	.1	
89			2.04	45.1	20.5	.1	
90			1.70	37.9	17.5	.1	Blowout (majority of swirl-can modules)
91			1.70	30.1	13.7	.086	Resonance (entire array pulsating)
92			1.53	27.0	12.3		
93			1.36	24.1	10.9		
94			1.19	21.2	9.6		
95			1.02	18.1	8.2		
96			.68	12.0	5.4		Blowout (all swirl-can modules)

TABLE IV. - COMBUSTOR PERFORMANCE TESTS FOR MODELS 7A AND 7B

[Pressure, 3 atm; nominal reference velocity, 100 ft/sec (30.5 m/sec).]

Run	Inlet air temperature		Air flow		Inlet Mach number	Fuel-air ratio	Average combustor outlet temperature		Combustion efficiency, percent	Combustor pressure loss, $\Delta P/P$, percent	Temperature distribution parameters		Pattern factor
	^{o}F	K	lb/sec	kg/sec			^{o}F	K			δ_{stator}	δ_{rotor}	
Model 7A													
1	580	577	29.09	13.19	0.2471	------	----	----	---	5.40	-----	-----	----
2	596	586	29.36	13.31	.2549	0.0099	969	793	56	5.61	0.916	0.641	0.75
3	599	588	28.64	12.99	.2505	.0113	1200	922	79	5.82	.485	.168	.38
4	593	584	29.16	13.22	.2525	.0127	1427	1048	98	6.09	.264	.037	.25
5	600	589	29.11	13.20	.2476	.0150	1601	1145	101	6.10	.208	.065	.23
6	594	585	28.31	12.84	.2493	.0165	1673	1185	100	6.08	.202	.075	.22
7	587	581	28.83	13.07	.2467	.0188	1810	1261	101	6.09	.201	.128	.24
8	599	588	29.37	13.32	.2478	.0208	1924	1324	102	6.07	.198	.079	.25
9	597	587	29.27	13.27	.2476	.0229	2094	1419	103	6.26	.253	.076	.26
10	596	586	29.03	13.16	.2476	.0231	2086	1414	102	6.22	.253	.082	.26
Model 7B													
1	616	597	29.10	13.19	0.2588	------	----	----	---	5.78	-----	-----	----
2	568	571	28.40	12.88	.2447	0.0104	1091	861	75	5.80	0.651	0.461	0.51
3	569	571	29.32	13.29	.2513	.0119	1358	1010	100	5.96	.216	.077	.26
4	573	573	29.00	13.15	.2544	.0162	1685	1191	105	5.94	.215	.053	.24
5	580	577	28.90	13.10	.2489	.0178	1786	1247	105	6.03	.264	.063	.28
6	572	573	29.00	13.15	.2479	.0200	1924	1324	105	6.10	.249	.064	.26
7	571	572	28.50	12.92	.2420	.0224	2053	1396	105	6.09	.231	.070	.24

Performance of Model 7 Combustors

Combustion efficiency. - Combustion efficiency was defined as the ratio of actual temperature rise to theoretical temperature rise. Combustor exit temperatures were mass weighted. The mass-weighted exit temperature was based on the total number of readings taken in the survey including those near the side walls of the combustor. Oxygen depletion resulting from vitiation of the combustion air was accounted for in combustion efficiency calculations.

The combustion efficiency of combustor model 7C at five reference velocities and at two inlet air temperatures is presented in figure 12 and table III(a). Combustion efficiency increased with increasing fuel-air ratio and generally decreased with increasing reference velocity with 600° F (589 K) inlet air temperatures. With 1150° F (894 K) inlet air temperature, combustion efficiency was essentially 100 percent and was not affected by fuel-air ratio or reference velocity. Combustion efficiencies often exceeded 100 percent for both inlet temperatures. It is believed that air leaks at the test section flange connec-

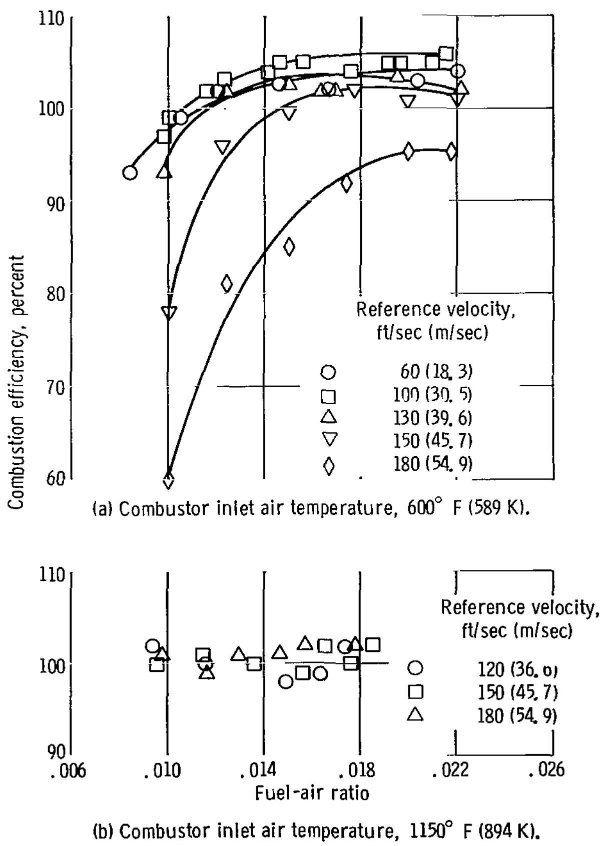


Figure 12. - Effect of operating conditions on combustion efficiency of model 7C. Combustor pressure, 3 atmospheres.

tions were primarily responsible. A leakage area of approximately 0.9 square inch ($5.8\ cm^2$) would account for about a 5-percent change in combustion efficiency. With a total flange seal length of 318 inches (8.07 m) this amount of leakage area was possible. Also, pressure checks prior to each run showed that leakage did occur. In general, the data indicated that combustion efficiency at these operating conditions should be no problem with this type of combustor.

Figure 13 shows the effect of swirler open area on combustion efficiency of model 7

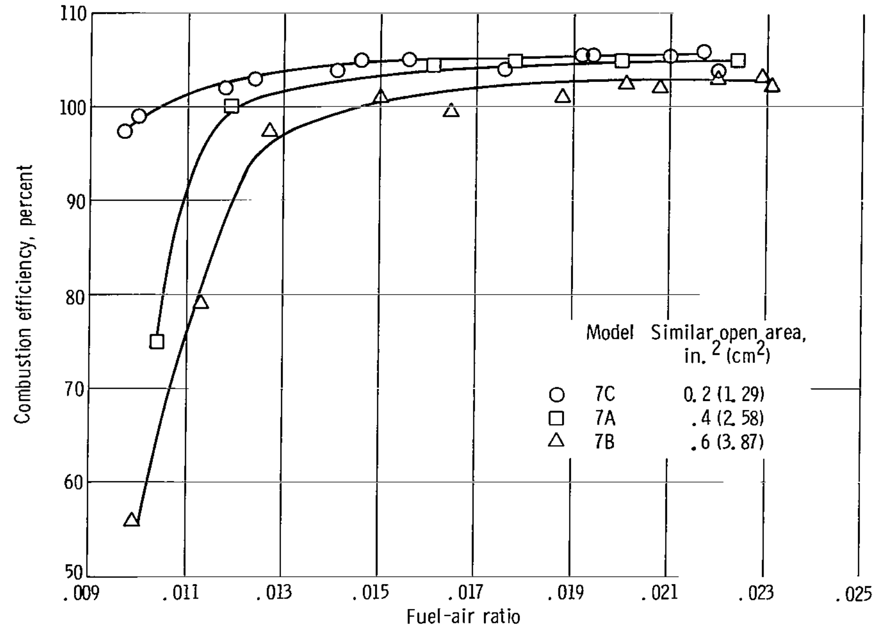


Figure 13. - Effect of swirler open area on combustion efficiencies of model 7 combustor designs. Combustor inlet pressure, 3 atmospheres; inlet temperature, 600° F (589 K); reference velocity, 100 feet per second (30.5 m/sec).

designs. The data for models 7A and 7B are presented in table IV. At fuel to air ratios of 0.013 or less, combustion efficiency decreased appreciably with increasing swirler open area. Although at higher fuel-air ratios combustion efficiency for all three models was 100 percent, Model 7C designs are preferable since they exhibited high efficiencies over the widest range of fuel-air ratios.

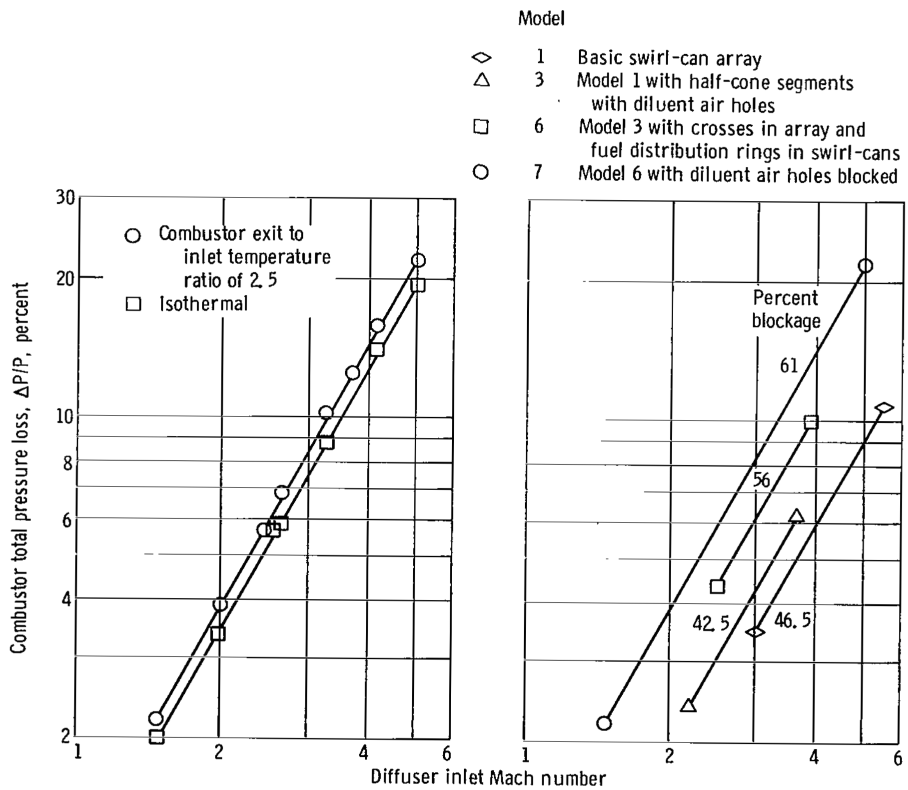
Total pressure loss. - Combustor total pressure loss $\Delta P/P$ includes the diffuser pressure loss and is defined by the following expression:

$$\frac{\Delta P}{P} = \frac{\text{Average diffuser inlet total pressure - average combustor exit total pressure}}{\text{Average diffuser inlet total pressure}}$$

Figure 14(a) and table III(a) present data which show the effect of diffuser inlet Mach number on total pressure loss $\Delta P/P$ for model 7C. At a diffuser inlet Mach number of 0.25 and a combustor exit to inlet temperature ratio of approximately 2.5, the pressure loss was 6 percent.

Figure 14(b) compares pressure loss for several of the combustor modifications investigated. Pressure loss was not dependent entirely on the amount of combustor blockage but was also dependent on where the blockage was placed. Generally, increases in combustor blockage along the top and bottom walls of the combustor produced greater increases in pressure loss than blockage increases within the array. Although the difference in blockage of models 3 and 6 was approximately 10 percent, and the difference in blockage of models 6 and 7 was 5 percent, one half as much, the change in pressure loss was about the same (2.5 percent). Increases in pressure loss generally caused better combustor exit temperature distributions.

Combustor exit temperature distribution. - An ideal combustor exit average radial temperature profile typical of those encountered in advanced engines was selected as a



(a) Combustor model 7C.

(b) Combustor models 1, 3, 6 and 7. Combustor exit to inlet temperature ratio, 2.5.

Figure 14. - Effect of diffuser inlet Mach number on pressure loss. Combustor pressure, 3 atmospheres; combustor inlet air temperature, 600° F (589 K).

basis for evaluating temperature distribution. Stress considerations of the turbine stator and rotor dictate the shape of the ideal profile in an actual engine. The following temperature distribution parameters were established to characterize combustor exit profiles:

$$\delta_{stator} = \frac{\left(T_{r,local} - T_{r,ideal}\right)_{max}}{\Delta T}$$

where $\left(T_{r,local} - T_{r,ideal}\right)_{max}$ is the largest temperature differential between the highest local temperature at any radius T_r, local and the ideal temperature for that radius. The ΔT is the average temperature rise across the combustor. The parameter δ_{stator} has significance in evaluating the degree to which the turbine stator will be affected by a poor temperature profile at the combustor exit.

$$\delta_{rotor} = \frac{\left(T_{r,av} - T_{r,ideal}\right)_{max}}{\Delta T}$$

where $\left(T_{r,av} - T_{r,ideal}\right)_{max}$ is the largest temperature difference between the average circumferential temperature on any radius and the ideal temperature for the radius. Since the turbine rotor tends to average circumferential variations, δ_{rotor} is a measure of the effect of a poor combustor exit profile on the turbine rotor. The terms radial and circumferential are used as though the test sections were annular sectors.

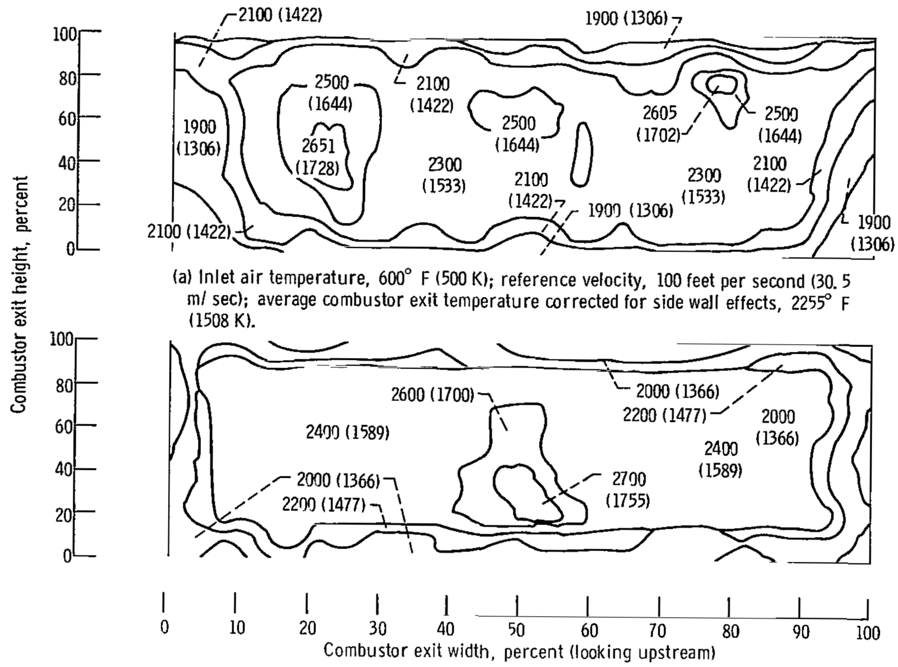
Another temperature distribution parameter commonly used in the aircraft industry was also employed. This parameter was the pattern factor and was defined as:

$$\text{Pattern factor} = \bar{\delta} = \frac{\text{Maximum local combustor exit temperature - average combustor exit temperature}}{\text{Average combustor exit temperature - average combustor inlet temperature}}$$

The pattern factor is a rougher measure of the quality of the temperature profile.

For calculations of δ_{stator}, δ_{rotor}, pattern factor, and average radial temperature profiles, approximately 10 percent of the temperature readings at each combustor side wall were disregarded to eliminate side wall effects which are not present in an annular combustor.

Temperature contours: Temperature contour maps at the combustor exit are presented in figure 15. Figure 15(a) shows a contour map obtained with 600° F (589 K) inlet air temperature, a reference velocity of 100 feet per second (30. 5 m/sec, and a fuel-air



(a) Inlet air temperature, 600° F (500 K); reference velocity, 100 feet per second (30.5 m/sec); average combustor exit temperature corrected for side wall effects, 2255° F (1508 K).

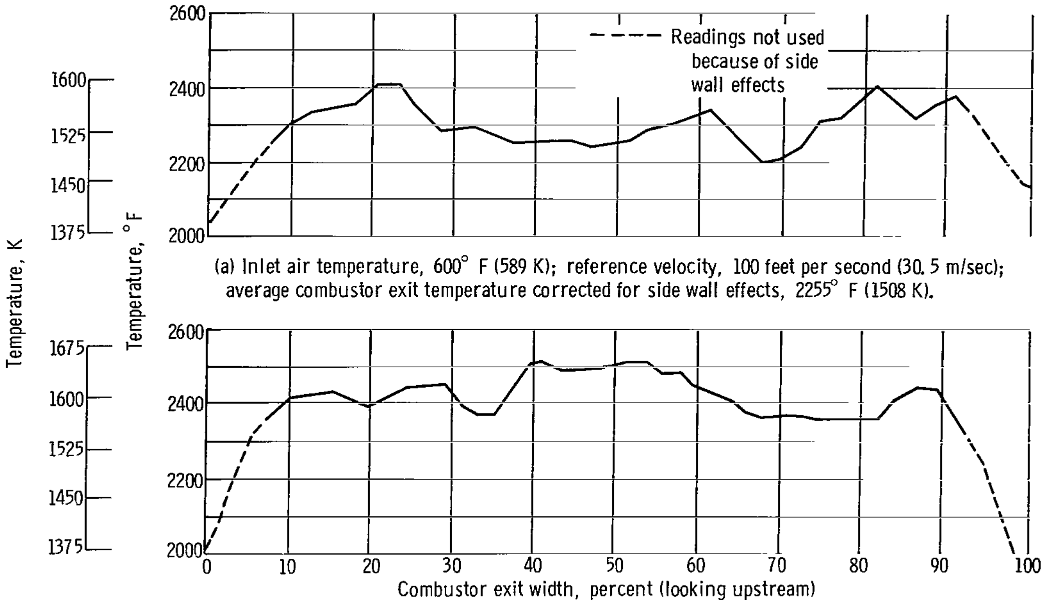
(b) Inlet air temperature, 1150° F (894 K); reference velocity, 150 feet per second (45.7 m/sec); average combustor exit temperature corrected for side wall effects, 2409° F (1594 K).

Figure 15. - Combustor exit temperature distribution contours of model 7C. Combustor pressure, 3 atmospheres; contour temperatures are given in °F (K).

ratio of 0.0232. The maximum temperature was 2651° F (1728 K) and the average temperature excluding 10 percent of the temperatures at each side wall was 2255° F (1508 K). The values of δ_{stator} and δ_{rotor} at this condition were 0.23 and 0.08, respectively. The pattern factor was 0.24. Approximately 75 to 80 percent of the area at the combustor exit was within a temperature differential of 360° F (455 K). Cold spots along the inner and outer combustor exit diameter were produced by air leaks through the liners of the constant-area section and ramp.

Figure 15(b) shows a contour map obtained with 1150° F (894 K) inlet air temperature, a reference velocity of 150 feet per second (45.7 m/sec), and a fuel to air ratio of 0.0185. The high inlet air temperature caused the liners to deform and allowed disproportionate amounts of inlet air to flow through the liners. This air leakage caused temperature readings near the upper and lower liners to be considerably lower than expected. Since the five center exit thermocouples better described temperature distributions at the combustor exit, only these center readings were used to compute the temperature distribution parameters. The values of δ_{stator} and δ_{rotor} for this condition were 0.20 and 0.05, respectively. The pattern factor was 0.19. The average temperature was 2409° F (1594 K). The area covered by the 5 center thermocouples (72 percent of the combustor exit height) was within a temperature differential of 322° F (161 K). Although average combustor exit temperatures were higher with 1150° F (894 K) inlet air, temperature distribution was improved. The data presented in table III(a) also show that increases in reference velocity impaired temperature distribution.

Average circumferential temperature profile: Combustor exit temperatures, averaged along a radius and plotted against circumferential position, are shown in figure 16 for the same combustor inlet conditions. Profiles again improved as the combustor inlet temperature was increased from 600° to 1150° F (589 to 894 K). For 600° F (894 K) inlet temperatures approximately a 200° F (93 K) span occurred between the highest and lowest average temperatures at all circumferential locations disregarding side wall effects. This span was lowered to 157° F (69 K) with 1150° F (894 K) inlet air temperature.

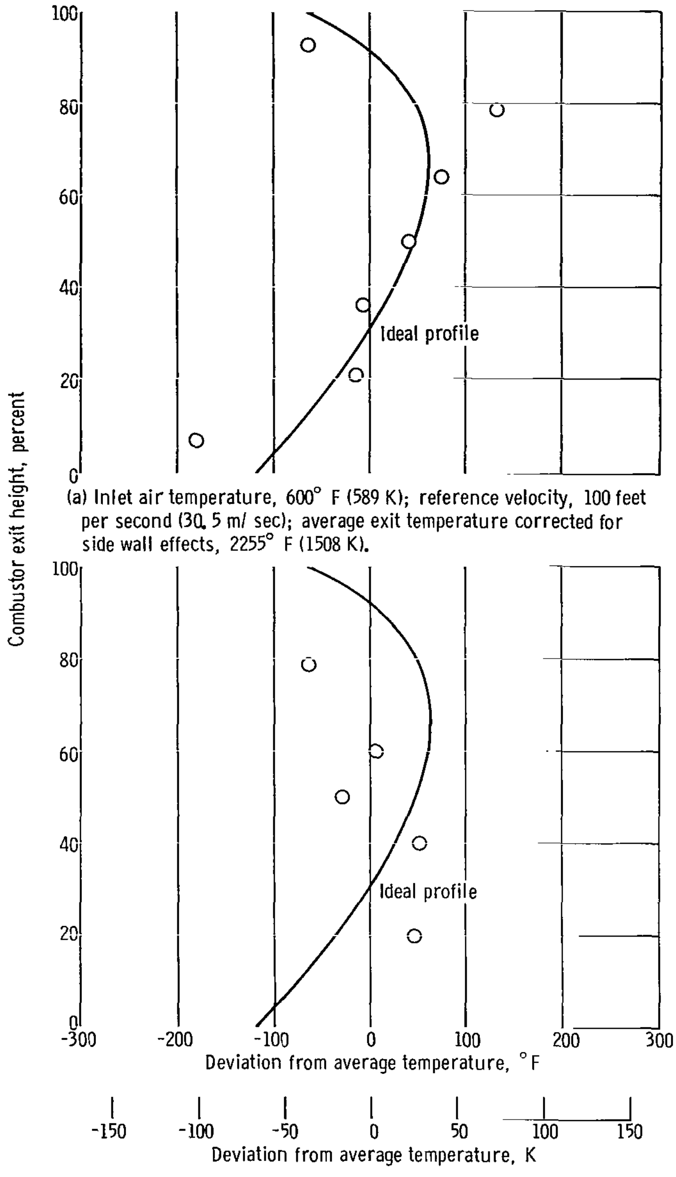


(a) Inlet air temperature, 600° F (589 K); reference velocity, 100 feet per second (30.5 m/sec); average combustor exit temperature corrected for side wall effects, 2255° F (1508 K).

(b) Inlet air temperature, 1150° F (894 K); reference velocity, 150 feet per second (45.7 m/sec); average combustor exit temperature corrected for side wall effects, 2409° F (1594 K).

Figure 16. - Average circumferential combustor exit temperature profile for model 7C. Combustor pressure, 3 atmospheres.

Average radial temperature profile: Average radial temperature profiles for model 7C at the same combustor inlet conditions are shown in figure 17. Here, at each radial position, combustor exit temperatures were averaged circumferentially. The difference between these values and the average temperature, for all seven radii for the 600° F (589 K) and five radial positions for the 1150° F (894 K) inlet air conditions, are plotted against radial position. Radial position is expressed as percentage of combustor exit height. The ideal radial profiles shown on these plots are representative of the require-



(a) Inlet air temperature, 600° F (589 K); reference velocity, 100 feet per second (30.5 m/ sec); average exit temperature corrected for side wall effects, 2255° F (1508 K).

(b) Inlet air temperature, 1150° F (894 K); reference velocity, 150 feet per second (45.7 m/ sec); average exit temperature corrected for side wall effects, 2409° F (1594 K).

Figure 17. - Average radial combustor exit temperature profile for model 7C. Combustor pressure, 3 atmospheres.

ments of advanced turbojet engines. At 600° F (589 K) inlet air temperature, a maximum positive deviation of 84° F (29 K) from the ideal values was measured, while at 1150° F (894 K) the maximum positive deviation was 80° F (27 K). Radial profiles approximated the ideal profile at both inlet temperatures. All of the model 7C data were obtained with the inner and outer rows of swirl-can modules receiving 1.5 times the fuel supplied to the center two rows.

Smoke tests. - A Von Brand meter was used to determine concentrations of smoke in combustor exhaust gases. Combustor exit gas samples were drawn through the movable probe, passed through a surge chamber, and then through Whatman No. 4 filter paper in the Von Brand meter. A rotometer downstream of the meter measured sampling rates. Sampling rates were controlled by valves upstream and downstream of the surge chamber. A reflective densitometer was used to analyze the smoke traces.

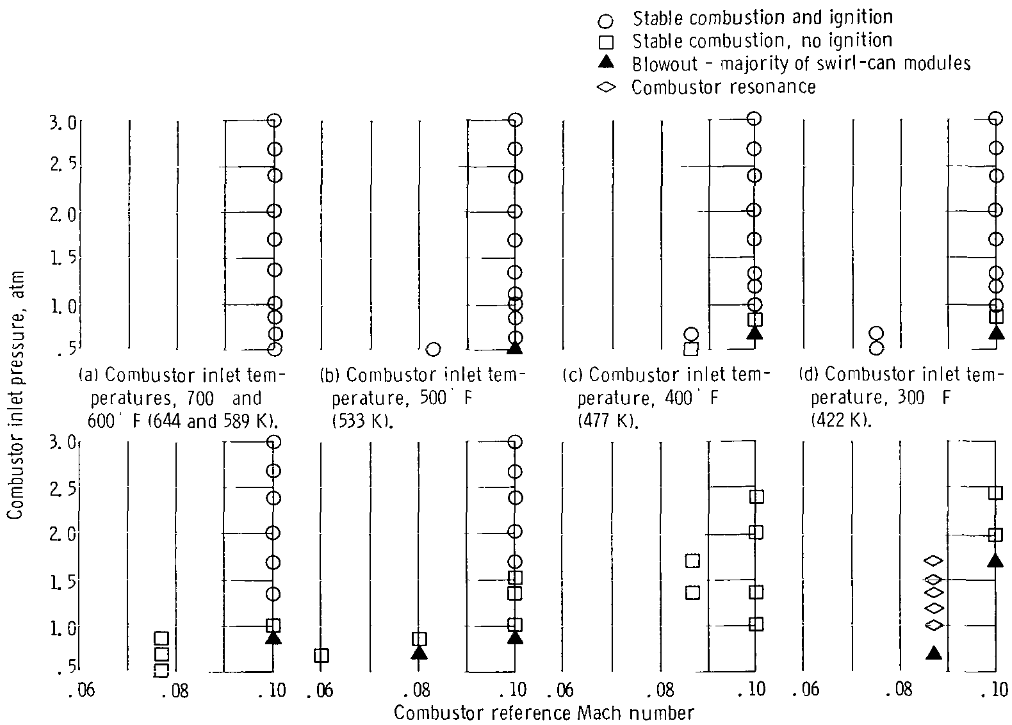
Test procedures employed for the smoke tests were those described in reference 8. A 5-pound (2.27-kg) pressure differential was set across the sampling paper which traveled at the rate of 4 inches per minute (10.16 cm/min). A combustor exhaust gas sample was passed through the paper at a rate of 0.6 cubic feet per minute (283.2 cm^3/sec) which produced a sample concentration of 0.3 cubic feet per minute per square inch of paper (21.95 $cm^3/(sec)(cm^2)$). A Proposed Smoke Number (PSN) defined in reference 8 was used to describe smoke levels. PSN is defined as $100(1 - R_S/R_W)$ where R_S is the relative reflectivity of the smoke sample and R_W is the relative reflectivity of the paper.

Results of smoke tests for combustor model 7C are presented in table III(b). No smoke was discovered at combustor inlet conditions of 3 atmospheres, 600° F (589 K), and a reference velocity of 100 feet per second (30.5 m/sec) and fuel to air ratios of 0.015, 0.020, and 0.022. Since the combustor pressure could not be increased above 3 atmospheres, the inlet air temperature was reduced to increase the probability of smoke formation. Again, no measurable smoke traces were discovered at inlet air temperatures as low as 150° F (339 K).

Since no measurable traces were found, Whatman No. 4 paper travel was stopped and a 1/4 by 1/2 inch (0.64 by 1.27 cm) section of paper was exposed to the combustor exhaust sample for 3 minutes. This resulted in a tape exposure 48 times greater than the previous method. Results showed no measurable smoke traces at inlet air temperatures of 600° and 400° F (589 and 477 K). At 300° F (422 K) a PSN of 2.2 was measured. The PSN increased to 11 with 200° F (366 K) inlet temperature and to 13 with 150° F (339 K) inlet air temperature.

Although extremely small amounts of smoke were discovered in the exhaust gases of model 7C combustors, results may not be indicative of smoke formation under actual flight conditions where pressures up to 6 times as great would be encountered. Reference 9 describes a method of extrapolating smoke data for comparative purposes with smoke data obtained at higher pressures. However, since combustor pressures were so low and smoke concentrations so slight, extrapolation of the data would produce highly questionable comparisons. Swirl-can combustors seem to be especially suited for low smoke formation since they control combustion carefully in many discrete burning zones.

Blowout and relight. - Altitude blowout and relight tests were also made. The purpose of these tests was to define approximate altitude reignition capabilities of swirl-can combustors. Tests were conducted over a range of combustor reference Mach numbers of 0.06 to 0.1, a fuel-air ratio of 0.015, and combustor inlet temperatures and pressures of 100° to 700° F (311 to 644 K) and 0.5 to 3.0 atmospheres. Testing proceeded in the following manner: At a preset inlet air temperature, combustor reference Mach number of 0.1, and a fuel-air ratio of 0.015, combustor inlet pressure was reduced until blowout occurred. If blowout occurred before a pressure of 0.5 atmosphere was reached, the combustor reference Mach number was lowered until stable combustion could be main-



(e) Combustor inlet temperature, 250° F (394 K).
(f) Combustor inlet temperature, 200° F (366 K).
(g) Combustor inlet temperature, 150° F (339 K).
(h) Combustor inlet temperature, 100° F (311 K).

Figure 18. - Altitude blowout and relight tests for combustor model 7C. Fuel-air ratio, 0.015.

tained down to 0.5 atmosphere. After combustion stability limits were defined, attempts were made to ignite the combustor as near to the blowout points as possible.

Results of blowout and reignition tests are given in figure 18 and table III(c). With a combustor reference Mach number of 0.1 and with combustor inlet air temperatures of 700° and 600° F (642 and 589 K) stable combustion was maintained over the entire range of of pressures. For inlet air temperatures of 500°, 400°, 300°, 250°, 200°, 150°, and 100° F (533, 477, 422, 394, 366, 339, and 311 K), stable combustion could not be maintained below pressures of 0.68, 0.85, 0.85, 1.0, 1.0, 1.0, and 2.0 atmospheres, respectively. Reducing combustor reference Mach number down to 0.06 allowed stable combustion to occur at low temperatures and pressures, although stable combustion could not be achieved below 0.68 atmosphere for temperatures of 200° F (366 K) or less. Resonance was encountered at 100° F (311 K) inlet air temperature with pressures under 1.7 atmospheres. During resonance the flames alternately were confined in the swirl-can modules and extended through the combustor exit plane. Pressure pulsations were readily observable.

Altitude relights were similarly affected by combustor inlet temperature, pressure, and combustor reference Mach number. With a combustor reference Mach number of 0.1, and with combustor inlet air temperatures of 700° and 600° F (642 and 589 K), ignition was achieved over the entire range of pressures. As inlet temperatures decreased to values of 500°, 400°, 300°, 250°, and 200° F (533, 477, 422, 394, and 366 K) ignition was achieved down to minimum pressures of 0.68, 1.0, 1.2, 1.35, and 1.7. Reduced combustor reference Mach numbers improved altitude relight but no ignition was achieved with inlet temperatures under 200° F (366 K).

In general, the swirl-can array performed well at the reduced inlet air temperature and pressure conditions. The flames were short and blue and no streaking was observed except at the resonance condition. No efforts to improve ignition such as increasing spark energy, relocating the spark plug, using a torch ignitor or increasing the fuel-air ratio were made. The spark plug extended through a side wall in a high velocity zone, possibly the worst location for relight. Similarly, no changes were made to individual swirl-can geometry to improve combustion stability.

SUMMARY OF RESULTS

A 48 swirl-can module combustor array was tested with ASTM-A1 fuel in a rectangular test section. The combustor housing height was 12 inches (30.5 cm) and the length from diffuser inlet to the combustor exit plane was 33 inches (83 cm). Tests were conducted at inlet air temperatures of 600° and 1150° F (589 and 894 K), a pressure of 3 atmospheres, and reference velocities of 60 to 180 feet per second (18.3 to 54.9 m/sec).

The best combustor, model 7C, produced the following results:

1. Combustion efficiencies near 100 percent were obtained for average combustor exit temperatures of 2200° F (1478 K).

2. The total pressure loss (including diffuser loss) was 6 percent at a diffuser inlet Mach number of 0.25 and a combustor exit to inlet temperature ratio of 2.5.

3. Combustor exit temperature distribution improved with increasing inlet air temperature. At an inlet temperature of 600° F (589 K), a fuel to air ratio of 0.0232, and a reference velocity of 100 feet per second (30.5 m/sec), the temperature distribution parameters δ_{stator} and δ_{rotor} had values of 0.226 and 0.082, respectively. The pattern factor $\bar{\delta}$ was 0.24 at an inlet air temperature of 1150° F (894 K), a fuel to air ratio of 0.0185 and a reference velocity of 150 feet per second (45.7 m/sec) the values of δ_{stator} and δ_{rotor} were 0.20 and 0.054, and $\bar{\delta}$ was 0.19.

4. No measurable traces of smoke were found in combustor exit gases when the combustor pressure was 3 atmospheres, the inlet air temperature was varied between 150° and 600° F (339 to 589 K), fuel-air ratios were varied between 0.015 and 0.024 and standard sampling techniques were used.

5. Altitude blowout and relight tests conducted at a combustor reference Mach number of 0.1 and a fuel-air ratio of 0.015 produced the following results. No blowout occurred with an inlet air temperature of 600° to 700° F (589 to 644 K) and with pressures as low as 0.5 atmosphere. Similarly, at pressures above 2 atmospheres and inlet air temperatures as low as 100° F (311 K) no blowout occurred. However, reference Mach numbers as low as 0.06 were required to maintain stable combustion when both pressures and inlet air temperatures were decreased to 0.5 atmosphere and 100° F (311 K).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 24, 1969,
720-03.

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